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DS03-005A

April 27, 2004

To: Commissioner of Patents

From: Stephen B. Ackerman Reg. No. 37, 761
28 Davis Avenue
Poughkeepsie, NY 12603

Re: Serial No. **10/764,920**
Filing Date: **1/26/04**
Invr(s): **A. Sibrai, et al**
Title: **High Q Linear Controlled Variable Capacitor**

Please enter the enclosed Certified Copy of European patent application number 04368005.7 (filed on January 14, 2004) in the file for the above-referenced US patent application, which claims priority to this European patent application.

Respectfully submitted,

Stephen B. Ackerman
Reg. No. 37,761

CERTIFICATE OF MAILING

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The attached documents are exact copies of the European patent application described on the following page, as originally filed.

Les documents fixés à cette attestation sont conformes à la version initialement déposée de la demande de brevet européen spécifiée à la page suivante.

Patentanmeldung Nr. | Patent application No. | Demande de brevet n°

04368005.7

Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets
p.o.

R C van Dijk

Anmeldung Nr:
Application no.: 04368005.7
Demande no:

Anmeldetag:
Date of filing: 14.01.04
Date de dépôt:

Anmelder/Applicant(s)/Demandeur(s):

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ALLEMAGNE

Bezeichnung der Erfindung/Title of the invention/Titre de l'invention:
(Falls die Bezeichnung der Erfindung nicht angegeben ist, siehe Beschreibung.
If no title is shown please refer to the description.
Si aucun titre n'est indiqué se referer à la description.)

High Q linear controlled variable capacitor

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High Q linear controlled variable capacitor

Technical field

The invention relates to a voltage controlled variable capacitor, and more particularly, to a variable capacitor, formed of a larger number of fixed capacitor segments and a corresponding number of switching elements, typically integrated with the capacitance controlling functions on an integrated semiconductor circuit.

Background art

One example of a voltage-controlled capacitor is a varactor diode. When a reverse voltage is applied to a PN junction, it creates a depletion region, essentially devoid of carriers, which behaves as the dielectric of a capacitor. The depletion region increases as reverse voltage across it increases; thus the junction capacitance will decrease as the voltage across the PN junction increases. However the characteristics are non-linear and are widely temperature and process dependent. There is also a significant leakage current problem. Varactor diodes must be operated below the junction breakdown voltage. The varactor diode is sometimes called a varicap.

Fig. 1a shows the principle of a varactor diode; **Fig. 1b** shows the control voltage to capacitance characteristics of said varactor diode and demonstrates the effects of temperature and process variations.

Another example is a switched capacitor chain, where capacitors are switched in parallel one after the other, thus increasing the capacitance step by step. The capacitors, when made of metal or polycarbonate structures, are far less sensitive to temperature and process deviations. **Fig. 2a** shows the basic circuit concept. However, as is demonstrated in **Fig. 2b**, there is only a "step-wise linear"

capacitance change over the control voltage, when the transistors **T1** to **T4** of **Fig. 2a** switch at the points **Sw T1** to **Sw T4** as shown in **Fig. 2c**. In addition the switching of the individual capacitors causes switching noise ("spikes") on the common circuit rails. Furthermore, while the switching transistor is kept in a flat switching ramp to smooth the switching steps, the transistor's resistance causes a Q-factor problem.

U.S. Patent 6,356,135 (to Rastegar) describes an electronically trimable capacitor having a plurality of branch circuits, each including a capacitor which may be selectively controlled by a switch to contribute or not to the net capacitance exhibited by the trimable capacitor. Operation of the switches is under direction of digital instruction.

U.S. Patent 5,514,999 (to Koifman , et al.) shows a differential switched capacitor circuit, comprising: multiple switched capacitor stages, coupled in a chain.

U.S. Patents 4,449,141 and 4,456,917 (to Sato, et al.) disclose a variable capacitor comprising a plurality of variable capacitor elements each having depletion layer control sections and a capacity reading section formed on a semiconductor substrate so that the capacity appearing at each capacity reading section varies in response to the bias voltage applied to the depletion layer control sections.

Summary of the invention

A principal object of the invention is to control the capacitance of a variable capacitor in a linear mode through a tuning voltage. A fundamental requirement is to achieve a high Q-factor at the same time.

In accordance with the objectives of this invention, a circuit to implement a voltage controlled variable capacitor, operating in a linear mode and maintaining high Q-factor is achieved. The variable capacitor arrangement comprises a set of small individual capacitors. Switching devices, in series to each of said capacitors, connect said capacitors in parallel, one after the other in a linear mode. An essential concept of the invention is the introduction of a linear control function that will drive said switching devices steadily from off-state to on-state. In

accordance with the objectives of this invention, the disclosed invention adds circuits and methods to linearize the capacitance change and to minimize the effect of parasitic resistance in the capacitor switching elements, which would degrade the Q-factor.

One key point to obtain a high Q-factor is to drive the capacitor-switching element, typically a FET-transistor, into minimum RDSon or maximum RDSoff, as the parasitic resistance is the reason for Q-factor degradation. Another key point to obtain highest possible Q-factor: only very few transistors (ideally only one) should be in the active operating mode, i.e. in RDSon–change-mode, all others are either fully switched on or fully switched off.

In a first solution according to the objectives of this invention, the linear control voltage to drive said capacitor-switching elements is derived from a circuit, implementing, for example, a chain of resistors, where each voltage point within said resistor chain controls one of said capacitor-switching elements. One endpoint of said resistor chain follows the tuning voltage input; all other voltage points follow a fraction of said tuning voltage.

In a second solution according to the objectives of this invention, a voltage follower circuit is introduced into the circuit of the first solution.

Furthermore, in a third solution according to the objectives of this invention, introduces a set of operational amplifiers, one for each capacitor-switching device. A resistor chain, or a similar circuit, produces a series of threshold points and each of said operational amplifiers compares the tuning voltage input with its dedicated reference voltage. While said switching transistor is kept within its active switching range (RDS changing mode) the resistance of the transistor linearly follows the input difference of said operational amplifier. Said operational amplifiers give all freedom in circuit dimensioning to decide on the preferred threshold values and steepness of the switching ramp.

There are various techniques to generate a set of reference values defining the threshold points for each of said amplifier stages. And there are various techniques to provide a tuning voltage, dedicated for the voltage controlled capacitance change, to all of said amplifier stages.

Depending on the technique to implement the reference values for each of the amplifiers within said operational amplifier chain, even specific nonlinear relations of capacitance change versus tuning voltage can be constructed.

In accordance with the objectives of this invention, a set of individual capacitors is implemented. Such capacitors could, for example, be discrete metal or polymer capacitors on a common planar carrier or they could be integrated on a semiconductor substrate. The switching device is typically a FET transistor, which could be for example a P-MOS or N-MOS junction FET or a P-channel or N-channel CMOS FET.

The series resistance of said active switching device degrades the Q-factor of the variable capacitor. With the proper choice of threshold and steepness of the switching ramp, the number of said switching devices being active concurrently can be kept to a minimum.

In accordance with the objectives of this invention, a method to control the capacitance of a variable capacitor in a linear mode through a tuning voltage and to achieve a high Q-factor at the same time generate, is achieved. One method is to switch a variable number of capacitors in parallel, where only very few (ideally only one) are in the active transition phase of being switched on in a continuous mode. All other capacitors of a larger number of capacitors are either already fully switched on or are still complete switched off. One key method is to control the switching function for each of said continual switching devices, when said switching device is in its dedicated active working area in a linear mode. A further method amplifies, by the means of an operational amplifier, the difference of the capacitance tuning voltage and said reference voltage of each amplifier stage, producing the linear control signal for said continually switching operation.

Another method generates a set of reference values, one for each of said amplifier stages. A tuning voltage is supplied to the circuit, dedicated for the voltage controlled capacitance change, to all of said amplifier stages.

Description of the drawings

In the accompanying drawings, forming a material part of this description, there is shown:

Fig. 1a (Prior Art) shows a simplified structure of a varactor diode;

Fig. 1b (Prior Art) shows the relation of the capacitor over tuning voltage change and shows the effects of temperature and process variation.

Fig. 2a, 2b and 2c (Prior Art) shows a principal circuit of a switched capacitor chain and the relation of the capacitor over tuning voltage change.

Fig. 3 shows a principal circuit of a switched capacitor chain, controlled through a chain of resistors.

Fig. 4a visualizes the theoretical concept, where only one switch is activated at one time.

Fig. 4b shows the relation of Q-factor over the tuning voltage for said theoretical concept, where only one switch is activated at one time.

Fig. 5a shows a simplified circuit of a single capacitor switching stage.

Fig. 5b shows the capacitance versus control voltage characteristics of said single capacitor switching stage.

Fig. 5c shows the Q-factor versus control voltage characteristics of said single capacitor switching stage.

Fig. 6a shows a simplified circuit of a single capacitor switching stage with a voltage follower circuit added.

Fig. 6b shows the RDSon characteristic of said single capacitor switching stage with the added voltage follower circuit.

Fig. 7 shows the gate voltage versus tuning voltage relation for the series of capacitor switching stages, according to Fig. 3.

Fig. 8 shows the Q-factor versus tuning voltage for the series of capacitor switching stages, according to Fig. 3.

Fig. 9 shows a circuit with operational amplifiers in the control signal path and with an alternative reference voltage circuit.

Fig. 10a visualizes the overlapping switching operations of the individual stages of Fig. 9.

Fig. 10b shows the RDSon resistance versus the transistor's gate voltage for a single capacitor switching stage of Fig. 9.

Fig. 11 shows, in more detail, the gate voltage versus tuning voltage relation for the series of capacitor switching stages, according to Fig. 9.

Fig. 12a shows the capacitance versus tuning voltage for the series of capacitor switching stages, according to Fig. 9.

Fig. 12b shows the Q-factor versus tuning voltage for the series of capacitor switching stages, according to Fig. 9.

Fig. 13 visualizes the overlapping switching operations of just 3 stages of the circuit according to Fig. 3.

Fig. 14 visualizes the overlapping switching operations of just 2 stages of the circuit according to Fig. 9.

Fig. 15 shows a realistic circuit diagram of an implementation, in accordance with an embodiment of this invention.

Fig. 16 visualizes the methods to control the capacitance of a variable capacitor in a linear mode through a tuning voltage and achieving a high Q-factor.

Description of the preferred embodiments

The objectives of this invention are to control the capacitance of a variable capacitor in a linear mode through a tuning voltage. A fundamental requirement is to achieve a high Q-factor at the same time.

A first solution to linearize the capacitance change is demonstrated in **Fig. 3**, where a rising control voltage, derived from the tuning voltage input through the resistor chain **R0** to **Rn**, switches on one transistor after the other (**T1** to **Tn**), thus switching capacitors **C1** to **Cn** in parallel. Only few (ideally only one) of said transistors are operating in their active transition phase. Ideally all other transistors are either fully off, i.e. RDSoff very high or the transistor is fully on, i.e.

RDSon very low. The resulting variable capacitance of the before mentioned arrangement is available between points **varCap1** and **varCap2**. In **Fig. 4a**, "switching on" the individual capacitors moves along the resistor chain (**switchRes**) and one transistor changes its resistance from zero to infinity (**changeRes**). **Fig. 4a** demonstrates a theoretical optimum, with some switches completely off, only one "switch" in an actual resistive state and all other remaining switches completely on. The resulting capacitance is **varCap**. Even with such theoretical optimum arrangement, the resistance of the active switch causes Q-factor to degrade, which is shown in **Fig.4b**. However, with real transistors, deviating from said theoretical ideal arrangement of switches (as shown in Fig. 4a), where RDSon is not zero and RDSoff is not infinite, Q-factor is further degraded considerably.

A single capacitor switching device, with **Vg** as the gate voltage to linearly control said switch as shown in **Fig. 5a,** has a capacitance **C** versus control voltage **Vg** characteristic as shown in **Fig. 5b**. The Q-factor **Q** versus control voltage **Vg** characteristic of such single switching device is shown in **Fig. 5c**.

In a second solution according to the objectives of this invention, improves the circuit by introducing a voltage follower circuit **Vf** into the circuit of the first solution, as shown in **Fig. 6a**. For a single stage RDSon is forced to a linear mode of operation following **Vramp** through the whole working range between the power supply lines. The resulting **RDSon** versus the control voltage **Vramp** is shown in **Fig. 6b**.

When a capacitor tuning voltage is applied to the circuit of **Fig. 3**, the gate voltage **V1** to **Vn** of each individual switching device changes with a fraction of said tuning voltage, as visualized with lines **Vg1** to **Vg5** of **Fig. 7**. The threshold points are marked **Th1** to **Th5** in **Fig. 7** and the distance between threshold points are marked **d1** to **d5**. A linear characteristic of the capacitance change is achieved when the resistors in said resistor chain in the circuit of **Fig. 3** are dimensioned to get threshold points with equal distance, i.e. when all threshold distances, symbolized as **d1** to **dn** in **Fig. 7**, are identical.

In a circuit that produces the individual control voltages for said capacitor switching devices with a mechanism similar to the resistor chain of **Fig. 3**, the next capacitor switching device in one stage starts to ramp up before the capacitor switching device in the previous stage reaches its endpoint. The ramps of both stages will therefore overlap. Said overlap, that increases with rising tuning voltage, will cause more and more switching devices to operate in their active working range, and as a result the Q-factor decreases continuously. The Q-factor degrading is shown in **Fig. 8**. Said increasing overlapping applies to a circuit according to **Fig. 3** and also to a circuit with voltage followers in the signal path, as of **Fig. 6a**.

In a third solution, a major improvement is achieved, by introducing an operational amplifier into the signal path, one for each capacitor-switching device. Further, the arrangement of the reference voltage circuit is considerably improved. A resistor chain, or a similar circuit, produces a series of voltage references and each of said operational amplifiers compares the tuning voltage input with its dedicated reference voltage. **Fig. 9** shows a principal diagram of such circuit. **Amp 1** to **Amp n** are said operational amplifiers, **Sw 1** to **Sw n** are the switching devices and **Cap 1** to **Cap n** are said capacitors that will be switched in parallel. **R1** to **Rn** build the resistor chain to produce references voltages **Ref 1** to **Ref n**. The resulting variable capacitance is available at the output points **varCap**.
While said switching transistor is kept within its active switching range (RDS changing mode) the resistance of the transistor linearly follows the input difference of said operational amplifier. Said operational amplifiers give all freedom in circuit dimensioning to decide on the preferred threshold values and steepness of the switching ramp.

The amplifiers need to slightly overlap to get a smooth linear capacitance curve, as shown in **Fig. 10a**. **Fig. 10b** visualizes the principal RDSon characteristic versus gate voltage of a single capacitor switching stage according to Fig. 9. A more detailed view on the individual ramp-up functions at the switching transistor's gate is shown in **Fig. 11**. **Vg1** to **Vg7** are the gate voltage

versus tuning voltage slope of the switching stages number 1 to 7 in this example. One can assume the active area of RDS changing to be between the 2 % point and the 98 % point. Compared to the characteristic of **Fig. 7**, all slopes of the individual gate voltages in **Fig. 11** are strictly parallel, which makes it easier to achieve the goal of linearity in the capacitor variation. Threshold points **Th1** to **Th7** in **Fig. 11** are equally spaced (distances **d1** to **d7** in **Fig. 11**).

A typical capacitance variation versus tuning voltage is shown in Fig **12a** and the corresponding Q-factor versus tuning voltage is shown in **Fig. 12b**.

Fig. 13 visualizes the overlapping switching operations of just 3 stages of the circuit according to Fig. 3. **Vg2**, **Vg3** and **Vg4** are the gate voltages of the 3 selected switching stages. **Overlap Vg3 – Vg2** is a measure, where **Vg3** just starts to switch on stage number 3 and where **Vg2** is still in the active working range for stage number 2. Similar, **Overlap Vg3 – Vg2** is a measure for the overlapping operation of switching stages number 4 and 3.

Fig. 14 visualizes the overlapping switching operations of just 2 stages of the circuit according to Fig. 9. **Overlap** is a measure, where **Vg2** just starts to switch on stage number 2 and where **Vg1** is still in the active working range for stage number 1. Because said gate voltage versus tuning voltage slopes are all in parallel, all overlaps are the same.

A major advantage of the circuit of **Fig. 9**, which uses operational amplifiers to compare tuning voltage to an individual reference voltage is, that all slopes of the gate control voltage and therefore the slopes of the RDSon variation are identical. Said slopes of the gate control voltage are shown in **Fig. 14**. In contrast to this, the slopes of the gate control voltage in a circuit, where a circuit produces the individual control voltages for said capacitor switching devices with a mechanism similar to the resistor chain of **Fig. 3**, all of said slopes are different. **Fig. 13** shows this typical behavior for the slopes of 3 neighboring stages

Fig. 15 shows a realistic circuit diagram of an implementation, in accordance with an embodiment of this invention. **Amp 1** to **Amp n** are said operational amplifiers, **Sw 1** to **Sw n** are the switching devices and **Cap 1** to **Cap n** are said

capacitors that will be switched in parallel, resulting in the total capacitance **varCap**. **R1** to **Rn** build the resistor chain to produce references voltages for the translinear amplifiers of each stage, as already shown in Fig. 9.

Depending on the technique to implement the reference values for each of the amplifiers within said translinear amplifier chain, even specific nonlinear relations of capacitance change versus tuning voltage can be constructed.
In accordance with the objectives of this invention, a set of individual capacitors is implemented. Such capacitors could be discrete metal or polymer capacitors on a common planar carrier or they could be integrated on a semiconductor substrate. The advantage of a capacitor not being of the junction (diode) type capacitor is the invariance due to voltage or temperature at the capacitor. The switching device is typically a FET transistor, which could be for example a P-MOS or N-MOS junction FET or a CMOS FET.

The method to achieve the objectives of this invention is illustrated in **Fig. 16**. First **(80)**, it starts with just the first capacitor, i.e. the count n=1 **(81)**. When the tuning voltage is rising **(82)** or is high enough **(83)**, the amplifier ramps up **(85)** and the switching device linearly switches on capacitor element n **(87)**. If the tuning voltage continues to rise **(90)** the amplifier continues to ramp up **(91)**. If however the tuning voltage turns down **(90)**, the amplifier will ramp down as well **(92)**. Once the tuning voltage reaches the upper limit of the active switching area **(95)**, the process ideally continues with the next step n = n + 1 **(97)(99)**. Depending on the direction of continued voltage change **(101)** it continues to ramp up or down. In case tuning voltage is lower than maximum for stage n **(84)**, the amplifier ramps down **(86)** and the switching device linearly switches on capacitor element n **(88)**. Once the tuning voltage reaches the lower limit of the active switching area **(96)**, the process ideally continues with the next step n = n + 1 **(98)(100)**. Again, depending on the direction of continued voltage change **(101)** it continues to ramp up or down and restarts at **(82)**.

CLAIMS

1. A circuit to control the capacitance of a variable capacitor in a linear mode through a tuning voltage and to achieve a high Q-factor at the same time; comprising:
- means for a set of individual small capacitors;
- means for a set of switching devices to continually switch on said capacitors in parallel, one for each of said small capacitors;
- means to linearly control the switching function for each of said set of continuous switching devices;
- means to generate a set of controlling signals, directly depending on the tuning voltage input, one for each of the capacitor switching stages;
- means to generate a set of threshold values, one for each of the capacitor switching stages; and
- means to provide a tuning voltage, dedicated for the voltage controlled capacitance change.

2. The circuit of claim 1 wherein said capacitors are discrete capacitor components.

3. The circuit of claim 1 wherein said capacitors are manufactured on planar carrier.

4. The circuit of claim 1 wherein said capacitors are integrated on a semiconductor substrate, but on a separate substrate than said switching devices.

5. The circuit of claim 1 wherein said capacitors are integrated on a semiconductor substrate and on the same substrate as said switching devices and amplifiers.

6. The circuit of claim 1 wherein said capacitors are manufactured as a Metal-Oxide structure.

7. The circuit of claim 1 wherein said capacitors are manufactured as a junction capacitor.

8. The circuit of claim 1 wherein said switching device is a transistor.

9. The circuit of claim 8 wherein said switching device is a P-MOS or N-MOS junction FET.

10. The circuit of claim 8 wherein said switching device is a CMOS FET.

11. The circuit of claim 1 wherein said means to linearly control the switching function for each of a set of continuous switching devices connect directly to said means to generate a set of controlling signals, directly depending on the tuning voltage input.

12. The circuit of claim 1 wherein said means to linearly control the switching function for each of said continuous switching devices use a circuit like a voltage follower to connect to said means to generate a set of controlling signals, directly depending on the tuning voltage input.

13. The circuit of claim 1 wherein said means to generate a set of controlling signals, directly depending on the tuning voltage input, one for each of said capacitor switching stages, is implemented a chain of resistors.

14. A circuit to control the capacitance of a variable capacitor in a linear mode through a tuning voltage and to achieve a high Q-factor at the same time; comprising:

- means for a set of individual small capacitors;
- means for a set of switching devices to continually switch on said capacitors in parallel, one for each of said small capacitors;
- means to linearly control the switching function for each of said continuous switching devices;

- means for a set of amplifier stages to produce said linear controls for said switching functions;
- means to generate a set of threshold values, one for each of said amplifier stages; and
- means to provide a tuning voltage, dedicated for the voltage controlled capacitance change, for all of said amplifier stages.

15. The circuit of claim 14 wherein said amplifier is an operational amplifier.

16. The circuit of claim 14 wherein said means to linearly control the switching function for each of said continuous switching devices is provided by the output of said operational amplifier.

17. The circuit of claim 14 wherein said means to generate a set of threshold values, one for each of said amplifier stages, is implemented as a chain of resistors.

18. The circuit of claim 14 wherein said means to provide a tuning voltage, dedicated for the voltage controlled capacitance change, is a signal connected to all amplifier inputs at the same time.

19. A method to control the capacitance of a variable capacitor in a linear mode through a tuning voltage and to achieve a high Q-factor at the same time generate; comprising:
- providing means for a set of individual small capacitors, means for a set of switching devices to continually switch on said capacitors in parallel, one for each of said small capacitors, means to linearly control the switching function for each of said continuous switching devices, means to generate a set of controlling signals, directly depending on the tuning voltage input, one for each of the capacitor switching stages; means to generate a set of threshold values, one for each of said capacitor switching stages, means to provide a tuning voltage, dedicated for the voltage controlled capacitance change, for all of said capacitor switching stages

- continually switching on one of said continuous switching devices in order to switch one of said small capacitors in parallel to the already switched on capacitors, one after the other;
- linearly controlling the switching function for each of said continuous switching devices;
- generate a set of controlling signals, directly depending on the tuning voltage input, to produce the linear control signal for said continually switching operation;
- generating a set of threshold values, one for each of said capacitor switching stages; and
- supplying a tuning voltage, dedicated for the voltage controlled capacitance change, to all of said capacitor switching stages.

20. The method of claim 19 wherein continually switching on one of said small capacitors in parallel to the already switched on capacitors applies to discrete capacitor components.

21. The method of claim 19 wherein continually switching on one of said small capacitors in parallel to the already switched on capacitors applies to capacitors manufactured on a planar carrier.

22. The method of claim 19 wherein continually switching on one of said small capacitors in parallel to the already switched on capacitors applies to capacitors integrated on a semiconductor substrate.

23. The method of claim 19 wherein linearly controlling the switching operation applies to a transistor as said continuous switching device.

24. The method of claim 23 wherein linearly controlling the switching operation applies to a P-MOS or N-MOS junction FET as said continuous switching device.

25. The method of claim 23 wherein linearly controlling the switching operation applies to a CMOS FET as said continuous switching device.

26. The method of claim 19 wherein amplifying the difference of the capacitance tuning voltage and the reference voltage of each amplifier stage to produce the linear control signal for said continually switching operation is performed by said operational amplifier.

27. The method of claim 19 wherein generating a set of threshold values, one for each of said amplifier stages uses a chain of resistors.

28. The method of claim 19 wherein supplying a tuning voltage, dedicated for the voltage controlled capacitance change, to all of said amplifier stages uses a signal connected to all amplifier inputs at the same time.

29. A method to control the capacitance of a variable capacitor in a linear mode through a tuning voltage and to achieve a high Q-factor at the same time generate; comprising:

- providing means for a set of individual small capacitors, means for a set of switching devices to continually switch on said capacitors in parallel, one for each of said small capacitors, means to linearly control the switching function for each of said continuous switching devices, means for a set of amplifier stages to produce said linear controls for said switching functions, means to generate a set of threshold values, one for each of said amplifier stages, means to provide a tuning voltage, dedicated for the voltage controlled capacitance change, for all of said amplifier stages
- Continually switching on one of said continuous switching devices in order to switch one of said small capacitors in parallel to the already switched on capacitors, one after the other;
- linearly controlling the switching function for each of said continuous switching devices;
- comparing the difference of the capacitance tuning voltage and the threshold voltage of each capacitor switching stage to produce the linear control signal for said continually switching operation;
- generating a set of threshold values, one for each of said amplifier stages; and

- supplying a tuning voltage, dedicated for the voltage controlled capacitance change, for all of said amplifier stages.

30. The method of claim 29 wherein comparing the difference of the capacitance tuning voltage and the threshold voltage of each capacitor switching stage to produce the linear control signal for said continually switching operation is performed by said operational amplifier.

ABSTRACT

A voltage controlled variable capacitor, formed of a larger number of fixed capacitor segments and a corresponding number of switching elements, linearly switches on each switching element, one after the other. Several techniques are disclosed to have only a minimum number of switching stages being in the active mode-of-change at any one time with a minimum overlap. The arrangement achieves a nearly linear change of capacitance versus tuning voltage change, while resulting in high Q-factor due to the low RDSon and high RDSoff of the fully switched stages.

Fig. 15

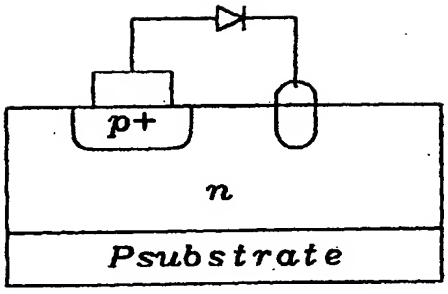

FIG. 1a – Prior Art

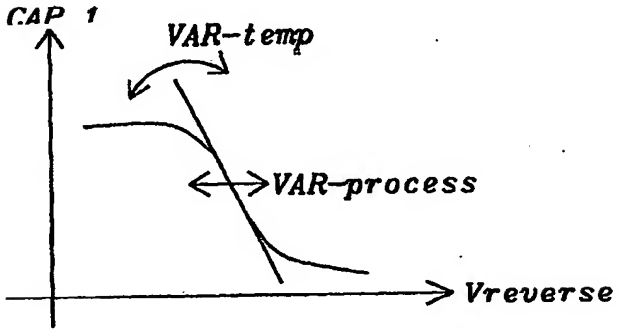

FIG. 1b – Prior Art

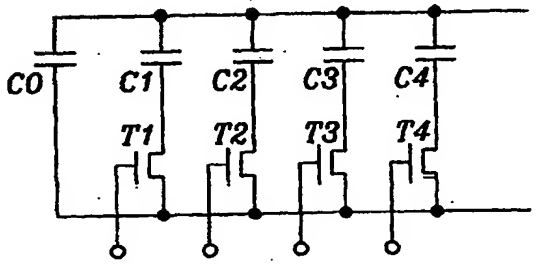

FIG. 2a – Prior Art

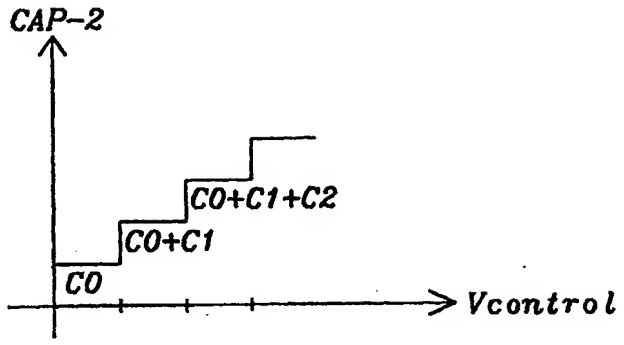

FIG. 2b – Prior Art

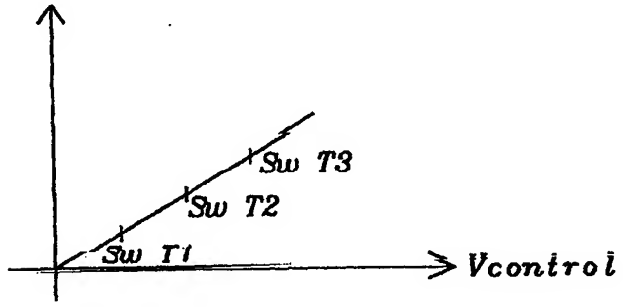

FIG. 2c – Prior Art

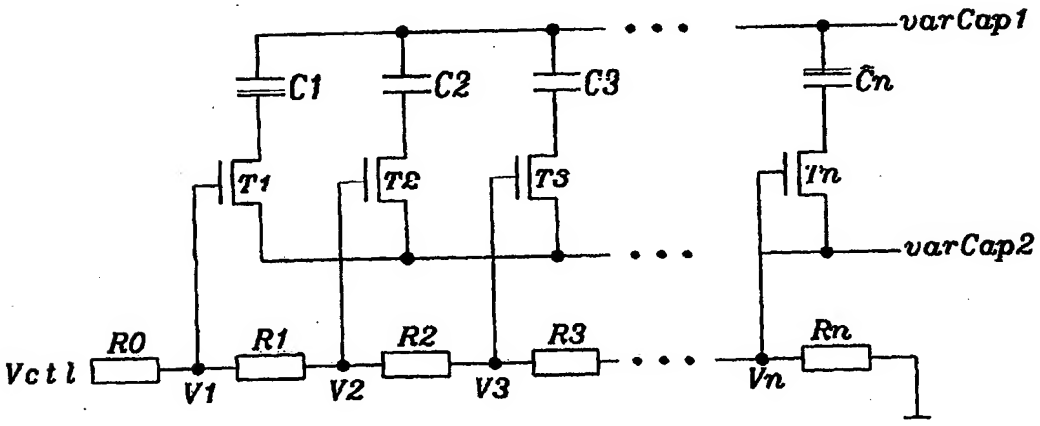

FIG. 3

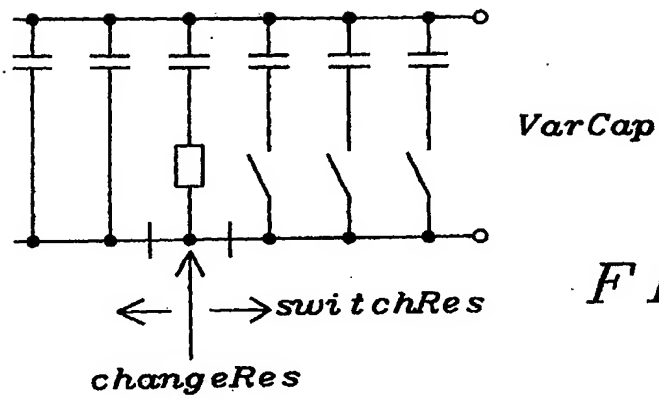

FIG. 4a

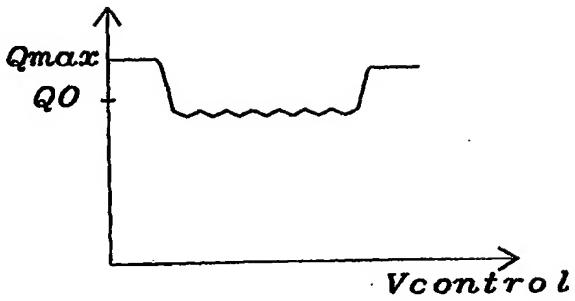

FIG. 4b

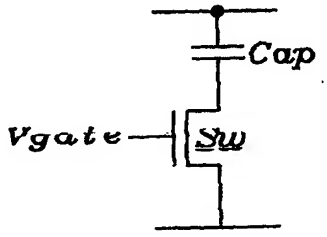

FIG. 5a

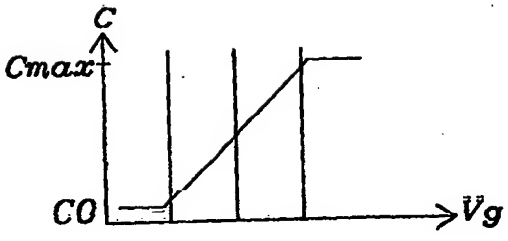

FIG. 5b

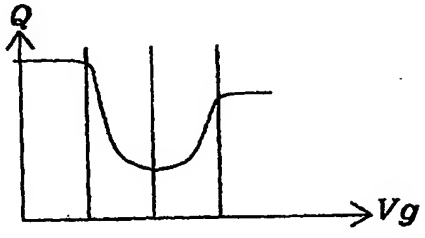

FIG. 5c

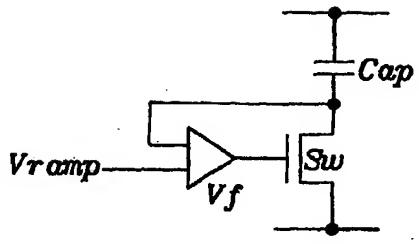

FIG. 6a

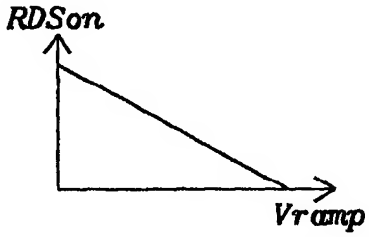

FIG. 6b

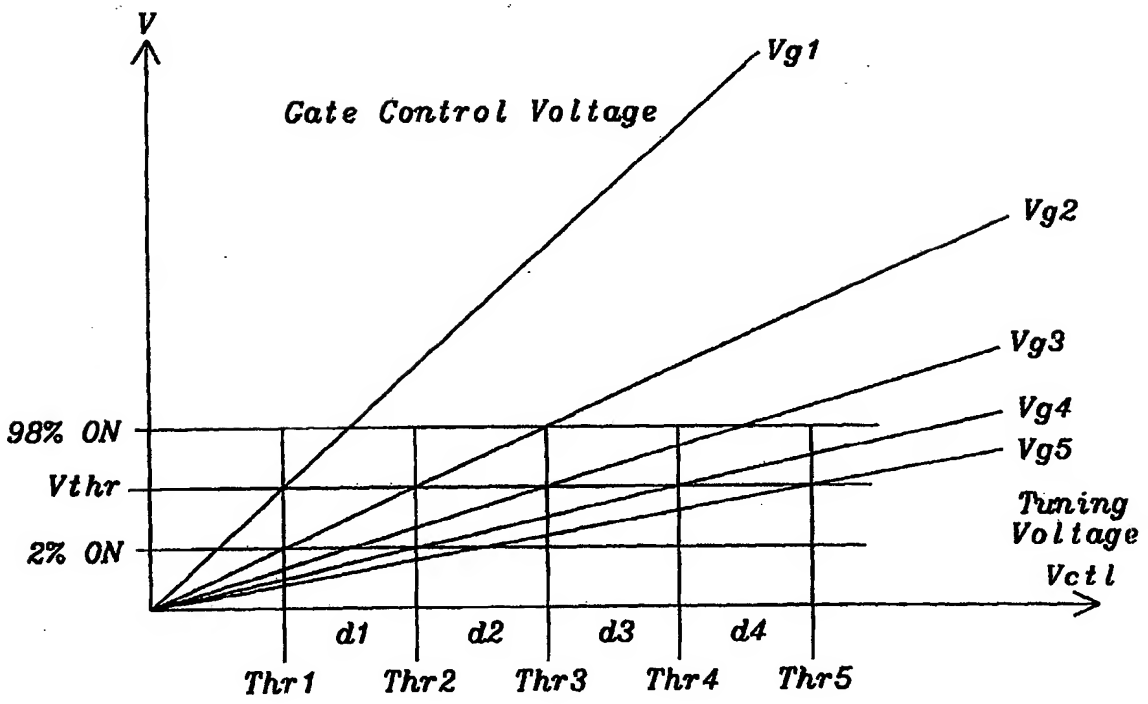

FIG. 7

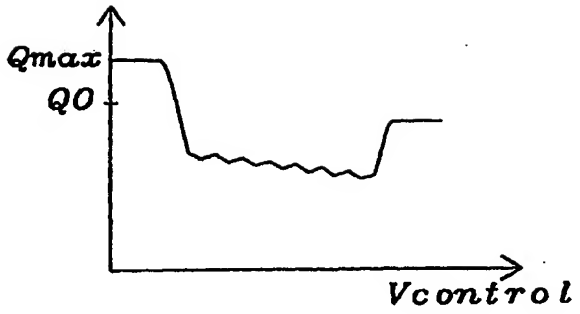
Qmax
QO
Vcontrol

FIG. 8

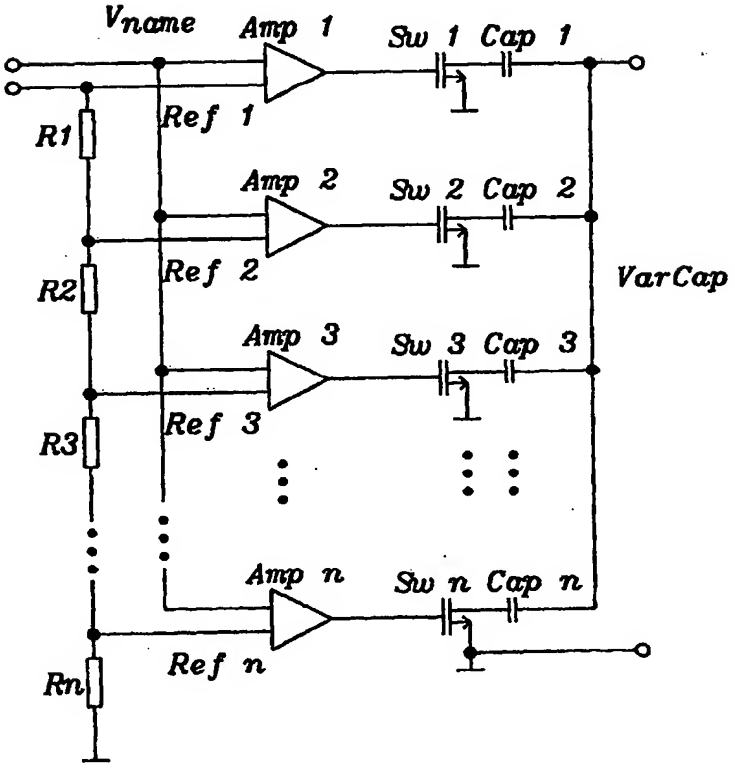
Vname
Amp 1
Sw 1
Cap 1
Ref 1
R1
Amp 2
Sw 2
Cap 2
Ref 2
R2
VarCap
Amp 3
Sw 3
Cap 3
Ref 3
R3
Amp n
Sw n
Cap n
Ref n
Rn

FIG. 9

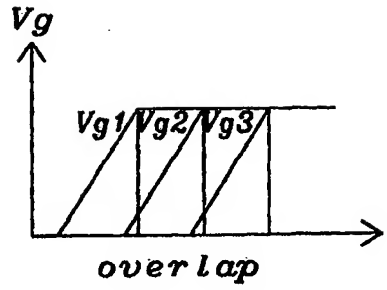

FIG. 10a

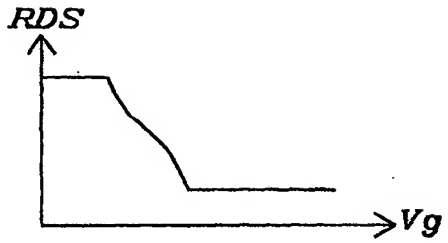

FIG. 10b

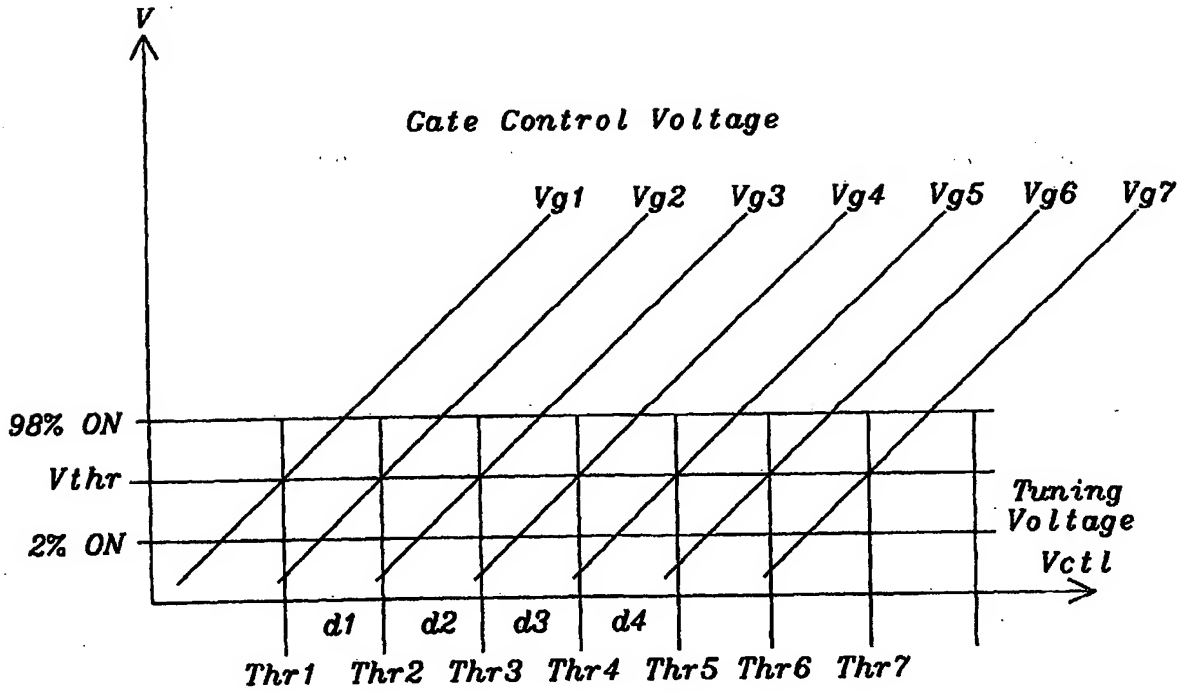

FIG. 11

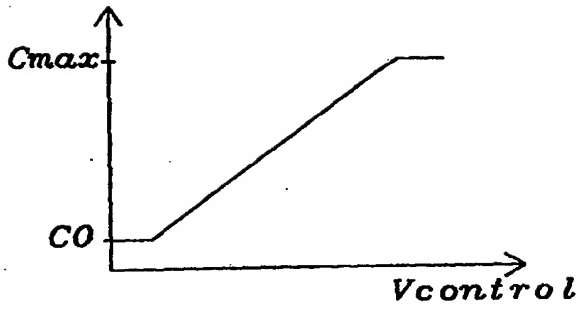

FIG. 12a

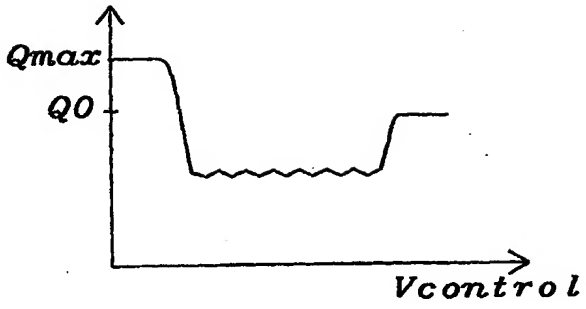

FIG. 12b

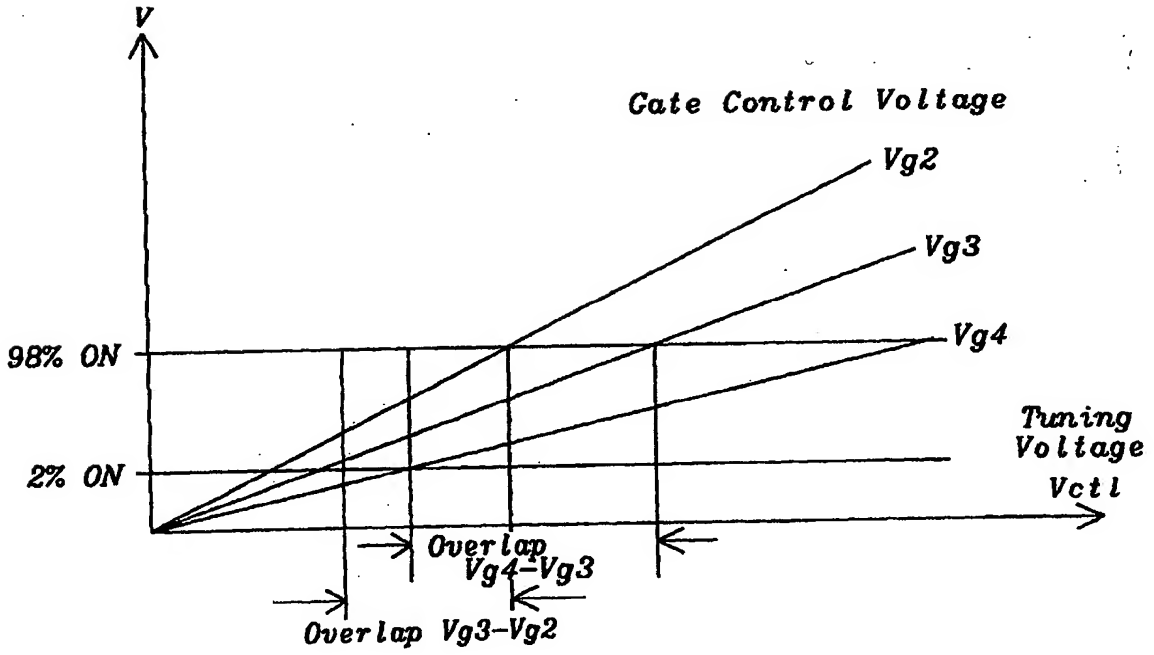

FIG. 13

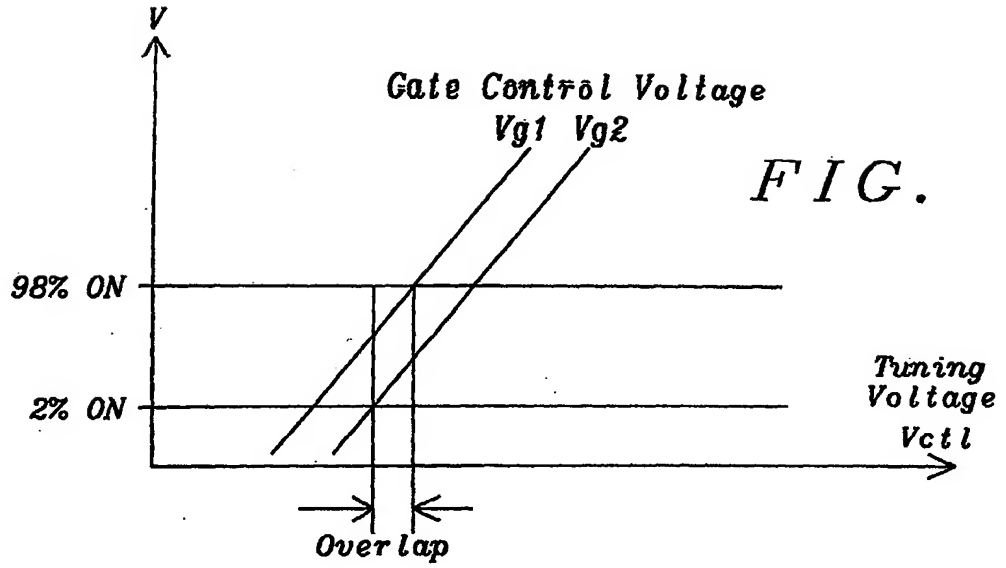
V
Gate Control Voltage
Vg1 Vg2
98% ON
2% ON
Tuning
Voltage
Vctl
Overlap

FIG. 14

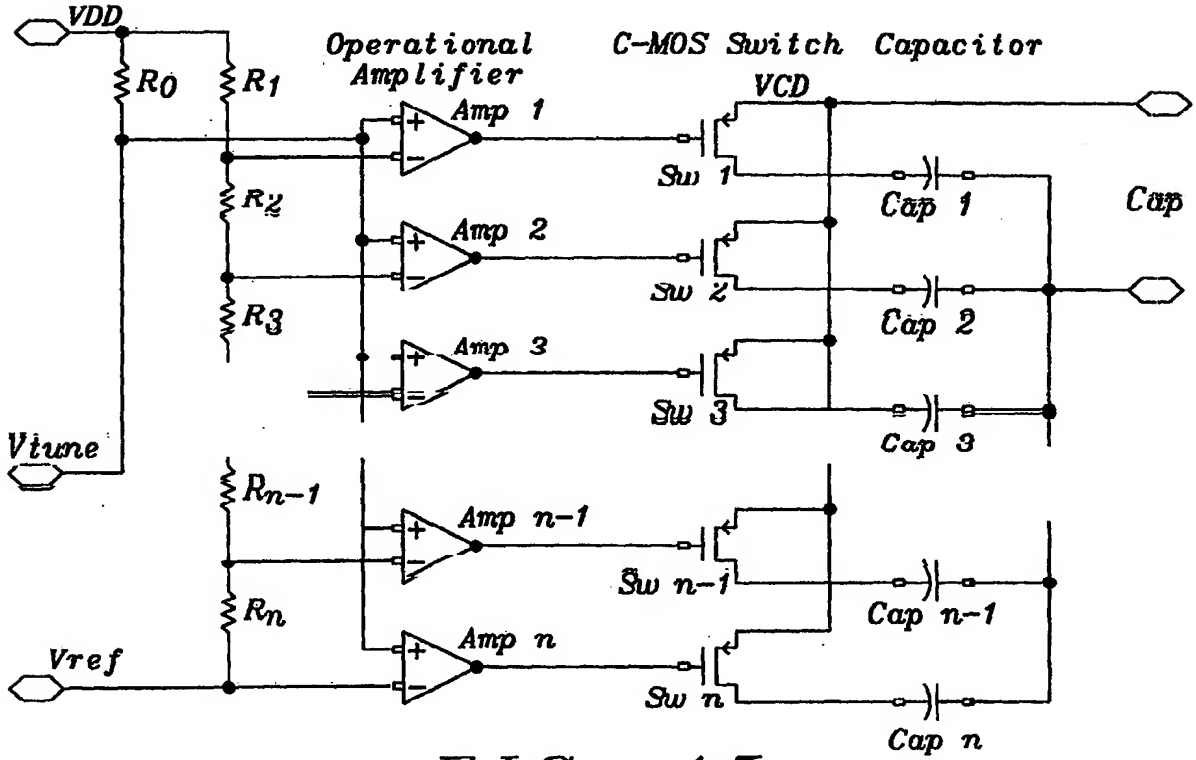
VDD
R0
R1
R2
R3
Operational
Amplifier
C-MOS Switch Capacitor
VCD
Amp 1
Amp 2
Amp 3
Sw 1
Sw 2
Sw 3
Cap 1
Cap 2
Cap 3
Cap
Vtune
Rn-1
Rn
Amp n-1
Amp n
Sw n-1
Sw n
Cap n-1
Cap n
Vref

FIG. 15

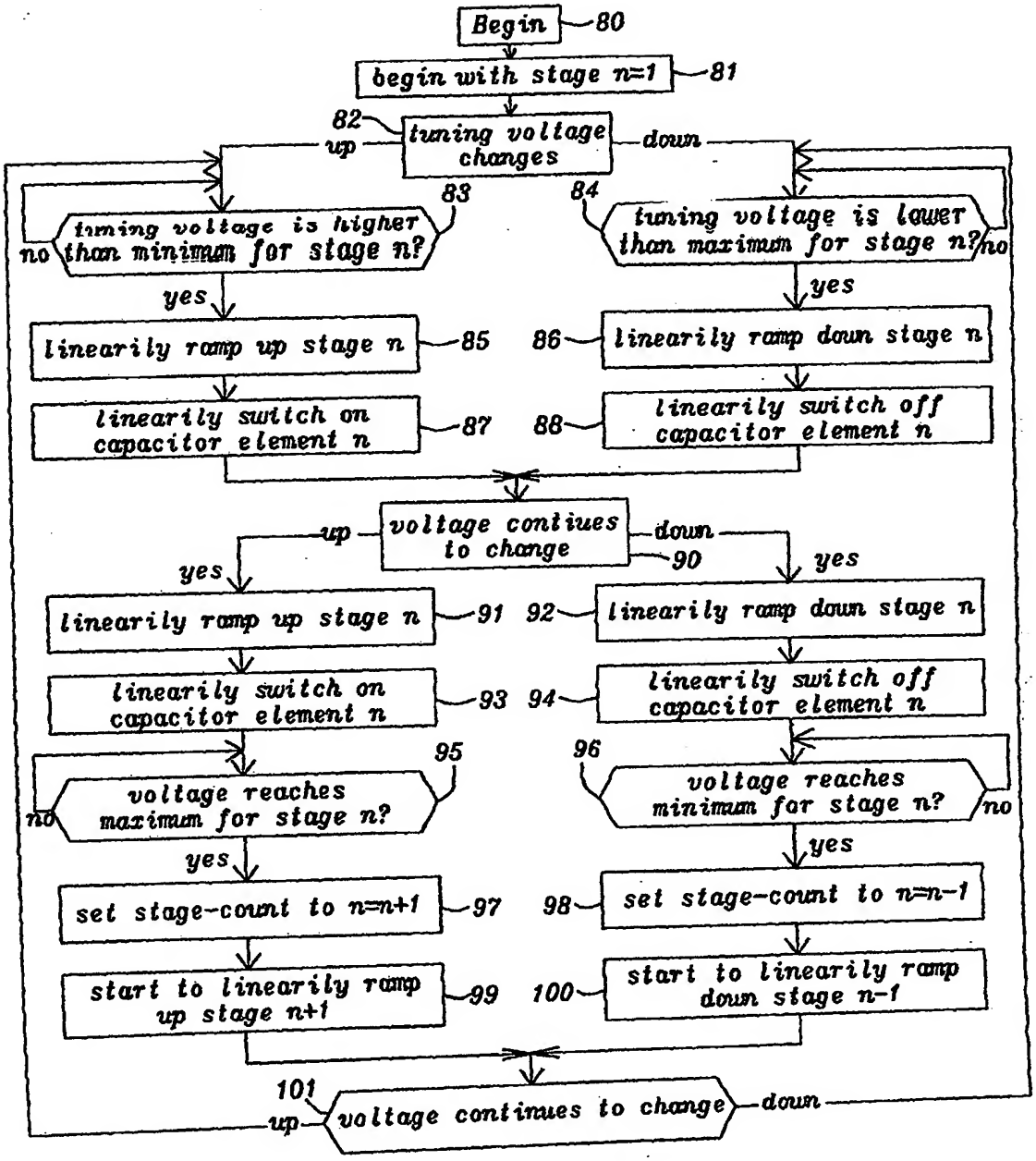
Begin
80
begin with stage n=1
81
82
tuning voltage changes
up
down
83
tuning voltage is higher than minimum for stage n?
no
yes
84
tuning voltage is lower than maximum for stage n?
no
yes
linearily ramp up stage n
85
86
linearily ramp down stage n
linearily switch on capacitor element n
87
88
linearily switch off capacitor element n
voltage contiues to change
up
down
90
yes
yes
linearily ramp up stage n
91
92
linearily ramp down stage n
linearily switch on capacitor element n
93
94
linearily switch off capacitor element n
95
voltage reaches maximum for stage n?
no
yes
96
voltage reaches minimum for stage n?
no
yes
set stage-count to n=n+1
97
98
set stage-count to n=n-1
start to linearily ramp up stage n+1
99
100
start to linearily ramp down stage n-1
101
voltage continues to change
up
down

FIG. 16